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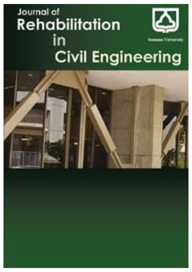


# The Experimental Investigation of Fatigue Life of Hot Mix Asphalt with Different Air Void Contents, Aggregate Type and Bitumen Grade at Low Temperature

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**ABSTRACT**

Fatigue behavior of Asphalt pavement is dependent on different parameters, including the bitumen, Aggregate, and mixture design. This study aims to investigate the effects of different air void contents of asphalt mixes prepared using two common bitumen types in Iran, 60/70 and 85/100, and limestone as well as silica aggregates on the fatigue life of the asphalt mixes at 5°C. First, the optimal amount of bitumen was calculated for each aggregate using the Marshall test. Then, to determine the fatigue behavior of the asphalt samples, indirect tensile tests were performed with controlled stresses at the levels of 100, 200, and 300 kPa. The results indicated that the 60/70 bitumen sample had a longer fatigue life than the 85/100 bitumen sample. The effect of the changing the bitumen type from 60/70 to 85/100 on fatigue life is more noticeable than the effect of the changing the air void content. Furthermore, it was revealed that lime aggregates have a higher fatigue life in comparison to silica aggregates, and the influence of increasing the air void content on fatigue life reduction is larger than that of changing the aggregate type. Eventually, some models were proposed to describe the fatigue life of asphalt mixes with different materials and different air void contents based on experimental studies and numerical analyses.

## 1. Introduction

The fatigue phenomenon is a factor that highly influences asphalt pavement life. The accurate identification of contributing factors in asphalt fatigue leads to enhancing pavement life. A fracture induced by the repetition of stress which is lower than the

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tensile strength of asphalt mixture is referred to as fatigue. The tires of vehicles deform the asphalt concrete layer when passing a specific place of the pavement. Such a deformation produces a strain below the asphalt layer. After a vehicle passes this place, the asphalt concrete layer tends to restore its previous state. By the repetition of this phenomenon**,** cracks form below the asphalt layer emerges when the tensile strain under the asphalt layer exceeds the tolerable strain of the asphalt layer. Such cracks move upwards through the asphalt layer over time. When the cracks join, the so-called fatigue cracks—a common failure in asphalt pavement—appear [1, 2].

Asphalt fatigue behavior is dependent on various parameters such as loading condition, test type, and asphalt material properties, making its interpretation complicated. The four-point bending test, three-point bending test, two-point bending test, triaxial test, direct tensile test, and indirect tensile test [1, 3, 4] are different experimental tests that are currently available to determine asphalt fatigue life.

Di Benedetto et al. [5] studied the fatigue behavior of asphalt mixes using five different experimental tests. It was shown that the test type considerably influences this behavior and the lowest fatigue life was related to the indirect tensile test.

There are various influential parameters on the fatigue life of a hot mix asphalt (HMA), among which temperature plays a significant role. The effect of temperature on the fatigue life of an asphalt mix is further dependent on how the test is performed. In terms of control type, fatigue tests can be classified into two groups: stress-controlled tests and strain-controlled tests. In stress-controlled approaches, temperature rise reduces the fatigue life [6, 7, 8]. On the other hand, in strain-controlled methods, an increase in the temperature improves the fatigue life of the asphalt mix [9, 10, 11].

Baladi [12] indicated that fatigue life increased by a coefficient of 1.79 as the temperature was decreased from 25°C to 6°C. However, a temperature rise does not always reduce the fatigue life, inasmuch as the magnitude of plastic deformation per the load unit is smaller at lower temperatures (i.e., stiff asphalt mixes) than at higher temperatures.

Arabani and Mirabdolazimi [13] attribute the reduced fatigue life of an iron power-modified HMA to the increased temperature caused by the high thermal conduction of iron and the high sensitivity of asphalt samples to temperature variation. They also reported that the high stiffness, coarse-surface, angled grains of iron powder, and the high elasticity modulus of steels enhanced the fatigue performance of HMA samples.

Numerous researchers have studied the effects of additives on the improvement of asphalt fatigue performance. A glass asphalt fatigue life model was presented by Arabani and Mirabdolazimi [14]. According to their results, the internal friction angle (φ) of the asphalt mix was higher due to the angled glass particles, which reduced the ultimate strain and prevented initial cracks and crack growth.

Shafabakhsh et al. [15] investigated the effect of $TiO_2$ nanoparticles on the fatigue life of asphalt samples. They reported that modifying bitumen by the addition of $TiO_2$ nanoparticles increased the tolerability of the samples against tensile strains. Additionally, Shafabakhsh et al. experimentally demonstrated that the addition of 7% of nano-silica particles to the asphalt binder increased the fatigue life of the asphalt mix by 2.3 times [16]. In [17], it was indicated that the fatigue behavior of modified nano particles increased the cohesion, adhesion, and fatigue strength of the asphalt mixes. It was also suggested that temperature rise results in a decrease of the fatigue life of asphalt mixes due to the high sensitivity of bitumen at high temperatures.

Another contributing factor in asphalt fatigue life is the air void content of asphalt mixes. In [12], it was indicated that an increase in the air void content of an asphalt mix diminishes the fatigue life. Mogawer et al. [18] performed a flexural beam fatigue test to explore the effect of asphalt density on fatigue life. They incorporated two aggregate gradations with the maximum nominal aggregate sizes of 9.5 mm and 12.5 mm. It was confirmed that the fatigue life of the asphalt mix with the maximum nominal aggregate size of 9.5 mm was significantly greater than that of the asphalt mix with the maximum nominal aggregate size of 12 mm. In other words, a decrease in the maximum nominal aggregate size enhances the bitumen content of the asphalt mix, increasing the fatigue life.

Abo-Qudais et al. [19] proposed a model to predict the fatigue life of HMAs based on their cumulative strain slope variation. In addition, they investigated the effect of gradation and loading on fatigue life. Three gradations with maximum diameters of 12.5 mm, 19 mm, and 25 mm and bitumen with penetration grades of 60-70 were used to prepare asphalt samples. They concluded that the larger the maximum diameter of the gradation is, the lower the fatigue life will be.

Wang et al. [20] studied the fatigue of asphalt binder and mastic samples at lower temperatures by direct tensile tests. A comparison of the difference between mastic asphalt results with the asphalt mix by X-ray CT images indicated that the fatigue strength of an asphalt mix is highly reliant on the air void content. Apart from that, utilizing coarse-grained aggregates in asphalt and mastic mixes increases voids in the mixes, and makes samples fail earlier under the fatigue test.

By employing indirect tensile tests, Al khateeb et al. [8] evaluated the loading frequency to the extent of failure. The tests were carried out at several loading frequencies, two different temperatures, and different stresses. The results demonstrated that the fatigue life of an asphalt mix went up with an increase in the loading frequency at both temperatures. The impact of loading frequencies was more profound at lower temperatures in the stress-controlled tests. Aside from that, at higher frequencies, the less loading stress became, the more increase rate of fatigue life produced.

A fatigue failure criterion was proposed by Nguyen [21]. They studied samples with a diameter of 50 mm and a thickness of 150 mm using indirect tensile tests. It was reported that the samples failed when the total length of fatigue cracks reached 15 cm. This criterion was proposed to be better representative of fatigue performance to the mean horizontal strain and vertical displacement criteria.

With regard to the effect of time on asphalt fatigue life, Al khateeb [22] observed that the longest fatigue life belonged to the sample that was maintained at 85°C for five days and tested at 40°C, while the lowest fatigue life was obtained for the sample that was maintained at 135°C for only 2 hours and tested at 20°C.

Das [23] examined the mechanical behavior of a dense-graded asphalt mixture under unaged, short-term, and extended aged circumstances. It is revealed that the role of the age factor diminishes with the increase in stress. Apart from that, the increasing of the test temperature and the moisture conditioning reduced the fatigue life of the asphalt mixture.

Regarding the comparison between the effects of loading frequency and aging degree on the fatigue performance of asphalt concretes, Liu [24] revealed that the one-day-old asphalt concretes had more acceptable fatigue life as well as more stable stress sensitivity compared to unaged asphalt concrete, and moreover, when the degree of aging is more than 1 day, with increasing degree of aging, the fatigue performance degenerated.

The results of Shafabakhsh studies showed the nano-silica improved the performance of the asphalt binder at high temperatures and lowered the efficiency at low temperatures. Fatigue test results also showed that the effect of polyurethane was better than nano-silica. [25].

Based on Shafabakhsh's study [25], the nano-silica improved the performance of the asphalt binder at high temperatures, and lowered the efficiency at low temperatures. Additionally, fatigue test results also showed that the effect of polyurethane was more significant than nano-silica's effect. Today, the engineering sciences are moving towards the use of databases, new experimental-theoretical methods and numerical methods to solve complex problems. So far, many studies have been done in the field of numerical analysis of the behavior of asphalt mixtures [26-34].

Comprehensive review of the previous studies indicates that the temperature, bitumen, air void content, and test type are salient parameters in terms of fatigue life. Aside from that, the indirect tensile test as a simple performance test was widely used in the literature. Moreover, utilizing high temperature conditions by most previous studies with 60/70 bitumen makes it justifiable to use bitumen with a higher penetration grade at low temperatures. To do so, in this paper, both 60/70 and 85/100 bitumen are considered at 5 ° C and indirect tensile tests are employed. Furthermore, the use of silica aggregate, which is less commonly used in experiments, is another innovation of this paper. Subsequently, a model is proposed for a realistic description of pavement fatigue life by numerical analysis.

## 2. Material description

The constituent aggregates of the mixture were silica and limestone, which have high moisture-failure resistance. The materials were provided by Qazvin Hot Mix Asphalt Plant, Iran. Table 1 provides the features of the materials. Since AASHTO 4 [35] gradation with the maximum nominal size of 12.5 mm is a widely-used gradation for the Topeka layer in Iran, it was employed to evaluate the fatigue performance of asphalt mixes. To achieve the gradation used in the Iran Road Pavement Code, i.e., AASHTO 4 gradation, the aggregates were sieved two times and collected in the required sizes. An estimation of the gradation is presented in Table 2. Two 60/70 and 85/100 bitumen types provided by Isfahan Oil Refinery were incorporated into this study. Table 3 presents the specifications of the bitumen types.

**Table 1.** Aggregate Properties.

| Property | Standard | Value | |
|---|---|---|---|
| | | Limestone | Silica |
| **Bulk specific gravity** | AASHTO T85 | 2.69 | 2.64 |
| **Water Absorption** | ASTM C127 | 1.68 | 1.15 |

**Table 2.** Gradation of the stone aggregates.

| **Sieve size** | 19mm | 12.5mm | 9.5mm | 4.75mm | 2.36mm | 0.3mm | 0.075mm |
|---|---|---|---|---|---|---|---|
| **Range** | 100 | 90-100 | - | 44-74 | 28-58 | 5-21 | 2-10 |
| **Passing** | 100 | 95 | - | 59 | 43 | 13 | 6 |

**Table 3.** Properties of bitumen used in this study.

| Property | Standard | Value | |
|---|---|---|---|
| | | 60/70 Bitumen | 85/100 Bitumen |
| **Specific gravity 25 °C (g/cm3)** | ASTM D70 | 1.02 | 1.01 |
| **Penetration (0.1 mm)** | ASTM D5-73 | 66 | 92 |
| **Ductility (cm)** | ASTM D113-79 | 112 | >100 |
| **Softening point (°C)** | ASTM D36-76 | 51 | 48 |
| **Flashpoint (°C)** | ASTM D91-78 | 262 | >225 |
| **Solubility in trichloroethylene %** | ASTM D1041-76 | 99 | 99.5 |

# 3. Tests

## 3.1. Marshall test

First, the optimal bitumen content was identified by the Marshall test, according to the ASTM D1559 standard. Then, fatigue tests were performed on the samples with their optimal bitumen contents, comparing the results [36].

## 3.2. Indirect tensile fatigue test (ITF)

After determining the optimal bitumen contents of the mixtures, the samples with 100 mm and 40 mm of diameter and thickness, respectively, were compacted based on the ASTM D1559 standard [28]. The indirect tensile fatigue tests of asphalt mixes were performed using a Nottingham machine at 5℃ and a loading frequency of 1 Hz with a stress-controlled approach under three stresses of 100, 200, and 300 kPa. The produced strain was continuously measured by two sensors until the samples failed. Finally, the failure cycle numbers and fatigue life were obtained (Table 4).

**Table 4.** Program for specimen preparation in the ITF test.

| **Parameter** | **Levels** |
|---|---|
| **Stress (kPa)** | 100, 200, 300 |
| **Air void contents (%)** | 3, 5, 7 |
| **Type of aggregates** | Silica, Limestone |
| **Type of bitumen** | 60/70, 85/100 |
| **Type of gradations** | Topeka |
| **Total number of samples** | 108 |

## 4. Results and discussion

### 4.1. Marshall test results

According to the standard, the optimum bitumen content has the highest Marshall strength, highest unit weight, and most suitable air void content. Such a bitumen content should be controlled by other parameters, including void filled with asphalt (VFA), void in mineral aggregate (VMA), and flow. With regard to the results, the optimal bitumen content of the lime materials built with 60/70 and 85/100 bitumen types was 5.5%. However, the optimal bitumen content of the silica materials built with 60/70 and 85/100 bitumen types was 5%. The difference in the optimal bitumen content arises from the aggregate structures. Lime aggregates are more porous than silica aggregates. This is why; lime aggregates absorb more bitumen, leading to higher optimal bitumen content.

### 4.2. Fatigue test results

Figs. 1 and 2 demonstrate the failure cycle number versus stress for silica-built samples. According to these figures, the increase of the air void content from 3% to 7% reduces the failure cycle number. In fact, the samples built with higher density (i.e., 75 blows on each side of the sample) exhibited higher fatigue resistance owing to the higher interaction of aggregates into each other. This result is in agreement with the reality that more voids in a mix can provide a more effective section for higher crack propagation. Apart from that, it is evident that a rise in the stress diminishes fatigue life.

Figs. 3 and 4 indicate fatigue failure cycle number versus ultimate strain for the silica-aggregated sample. As can be seen, the 60/70 bitumen-built samples had longer fatigue life than the 85/100 bitumen-built samples. Hence, it can be concluded that asphalt samples with higher viscosity have longer fatigue life in a stress-controlled condition. Moreover, a comparison of the results suggests that the bitumen penetration grade has a greater effect compared to the air void content on the fatigue life, in that the 60/70 bitumen-built sample with the air void content of 5% had a longer fatigue life than the 85/00 bitumen-built sample with the air void content of 3% at the same stress level.

Generally, the more the air content of lime-aggregated asphalt samples built with both bitumen types became, the lower number the failure cycle became (Figs. 5 and 6), likewise silica-aggregated asphalt samples.

The difference between the fatigue reduction rate of lime-aggregated and silica-aggregated samples is discernible in the fatigue test outcomes.

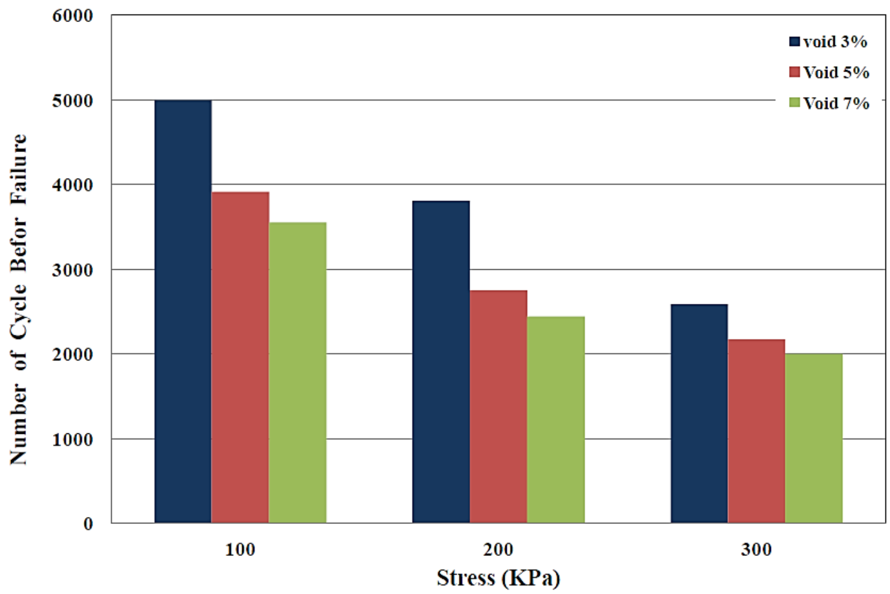


**Fig. 1.** Failure cycle number versus stress for 60/70 bitumen-built silica-material samples with air void contents of 3%, 5%, and 7%.

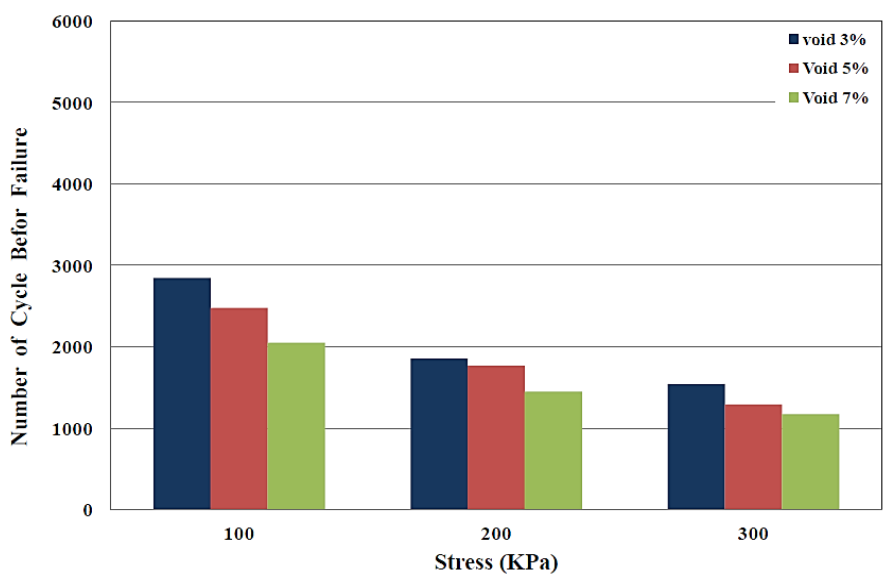


**Fig.2.** Failure cycle number versus stress for 85/100 bitumen-built silica-material samples with air void contents of 3%, 5%, and 7%.

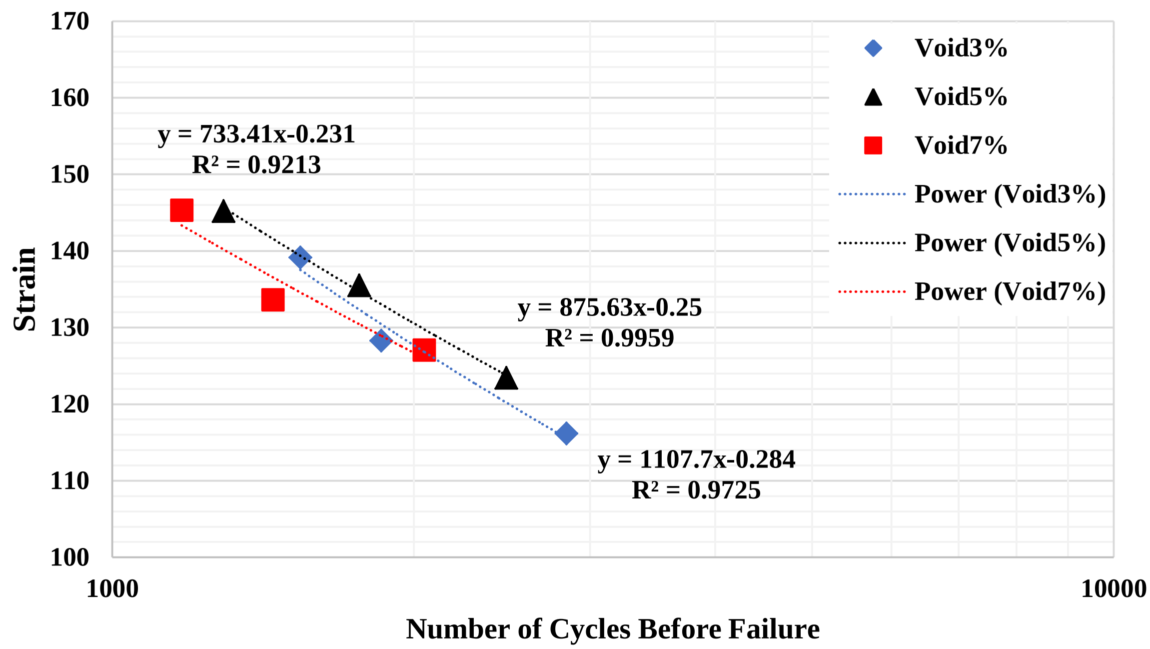


**Fig.3.** Failure cycle number versus ultimate strain for 85/100 bitumen-built silica-material asphalt samples.

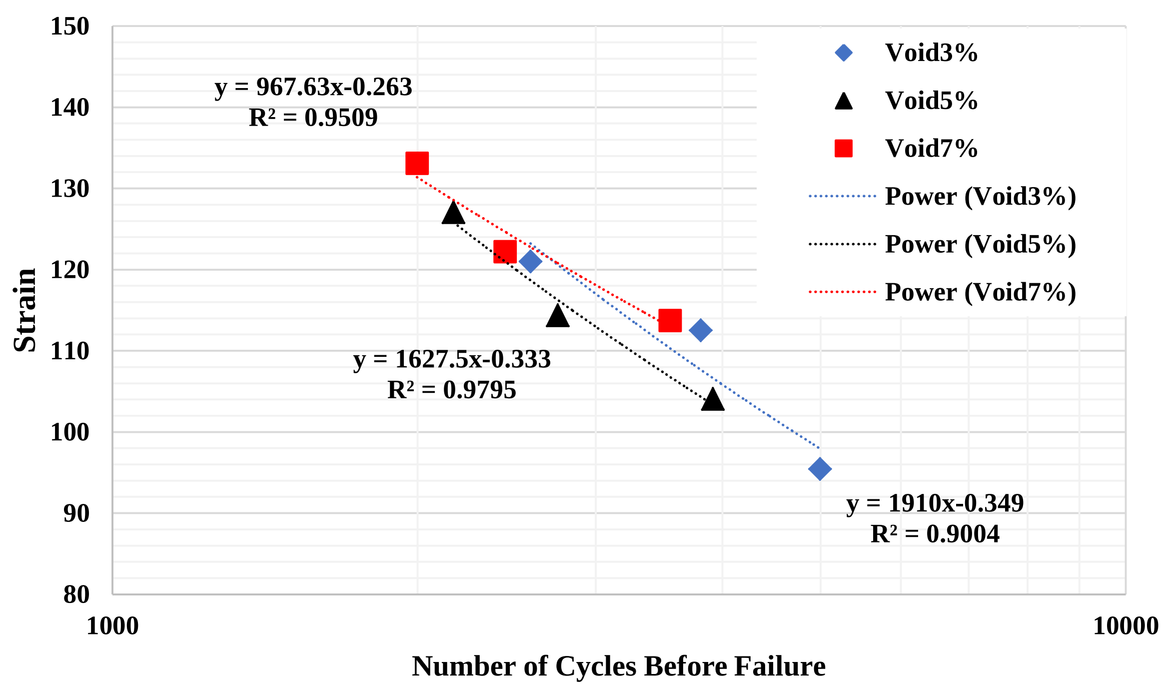


**Fig.4.** Failure cycle number versus ultimate strain for 60/70 bitumen-built silica-material asphalt samples.

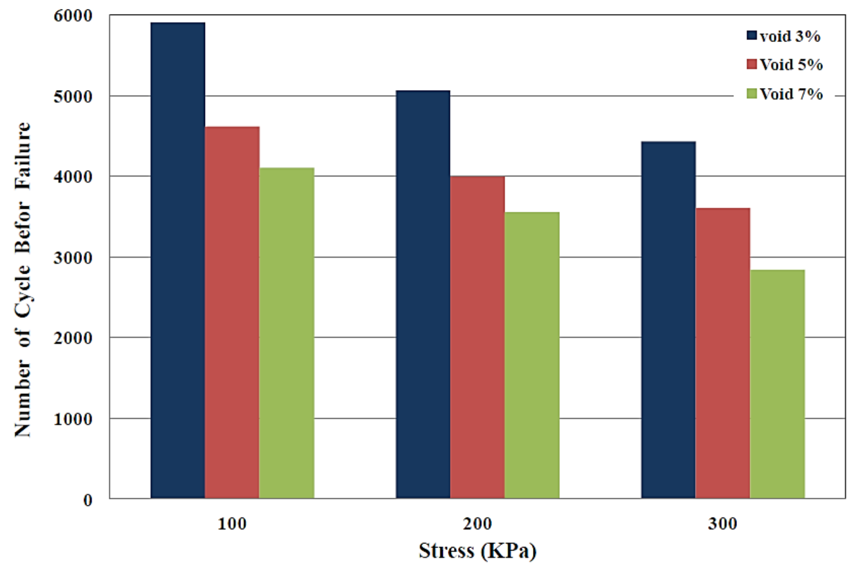


**Fig. 5.** Failure cycle number versus stress for 60/70 bitumen-built lime-material samples with air void contents of 3%, 5%, and 7%.

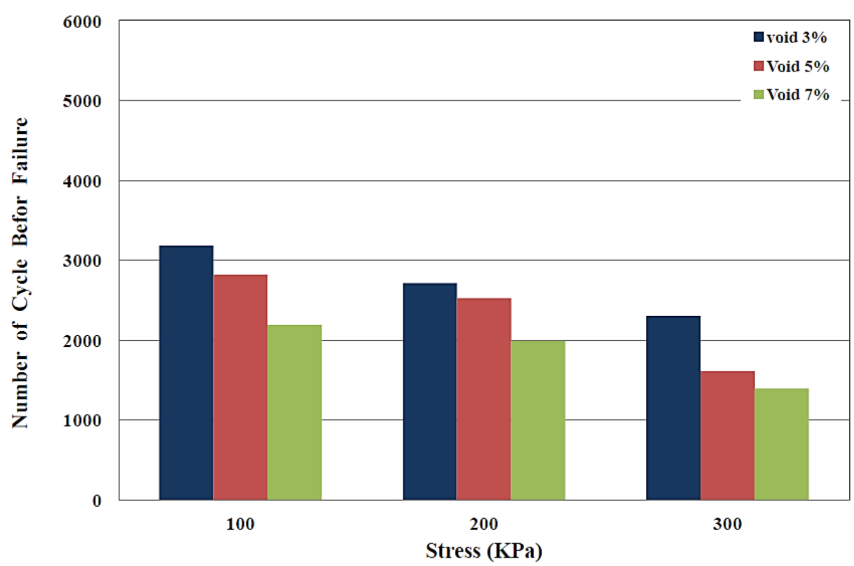


**Fig. 6.** Failure cycle number versus stress for 85/100 bitumen-built lime-material samples with air void contents of 3%, 5%, and 7%.

From Figs. 4 and 7, it can be seen that, in general, lime-aggregated samples had longer fatigue life than silica-aggregated samples. At high loading stress, the difference in the failure cycle number is more noticeable. The greater fatigue life of lime-aggregated asphalt mixes arise from their aggregate structures and minerals. According to the obtained results, the role of the air void content rise is of higher importance in comparison to the aggregate type role in terms of fatigue life decline. For example, the fatigue life of the 60/70 bitumen-built silica-aggregated mix with the air void content of 3% (see Fig. 4) is greater than that of the 60/70 bitumen-built lime-aggregated mix with the air void content of 5% (Fig. 7).

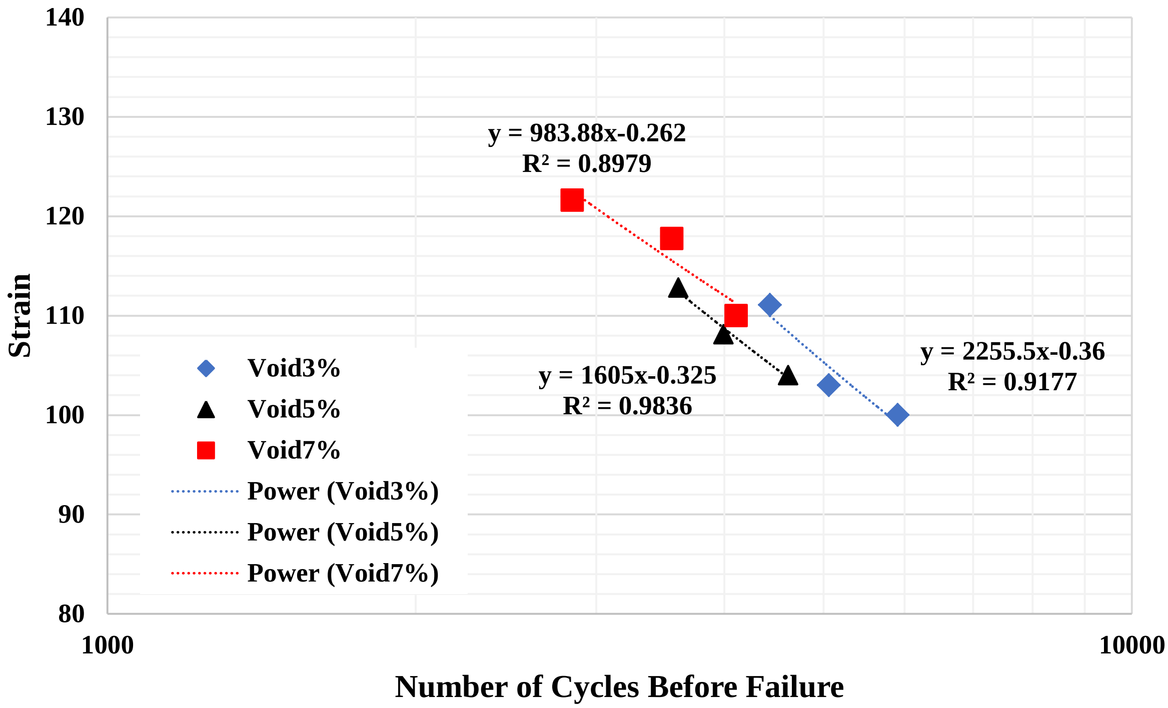


**Fig. 7.** Failure cycle number versus ultimate strain for 60/70 bitumen-built lime-material asphalt samples.

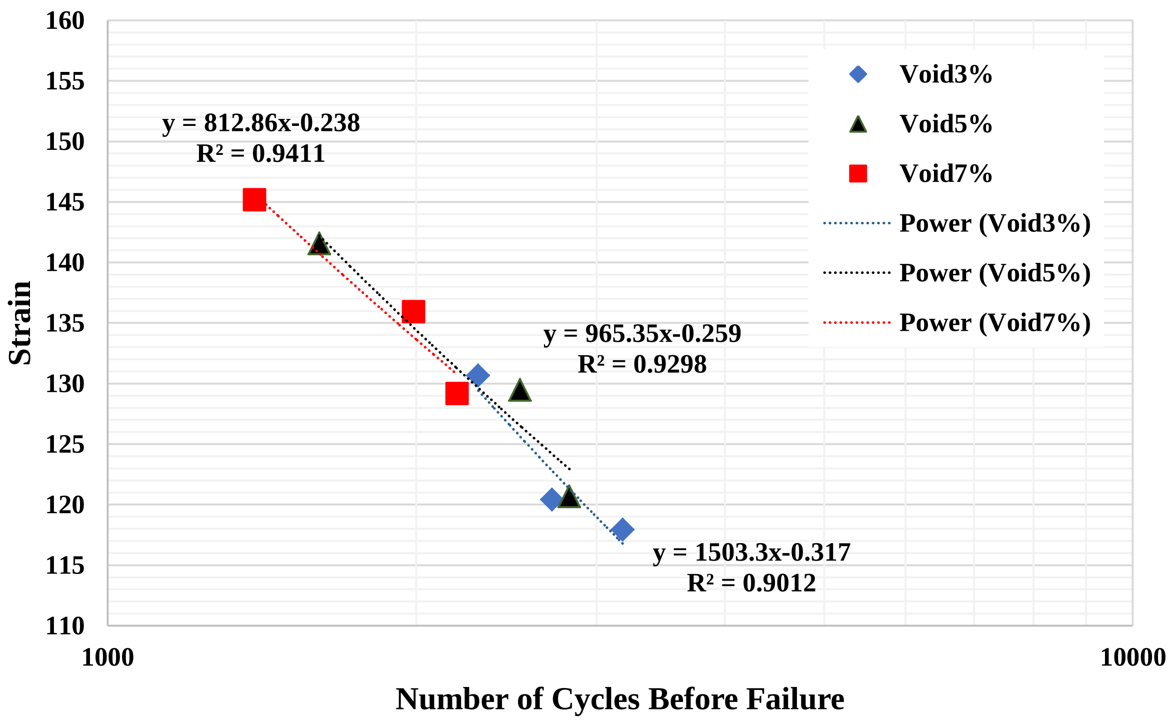


**Fig. 8.** Failure cycle number versus ultimate strain for 85/100 bitumen-built lime-material asphalt samples.

Fig. 9 depicts the diagram of the failure cycle number versus stress for the entire asphalt samples. According to this figure, in the fatigue test performed at 5°C, the highest failure cycle number and lowest failure strain were obtained for the lime aggregate sample made from 60/70 bitumen with the air void content of 3% at 100 kPa. On the other hand, the lowest failure cycle number and highest failure strain were derived for the silica aggregate sample made from 85/100 bitumen with the air void content of 7% at 300 kPa.

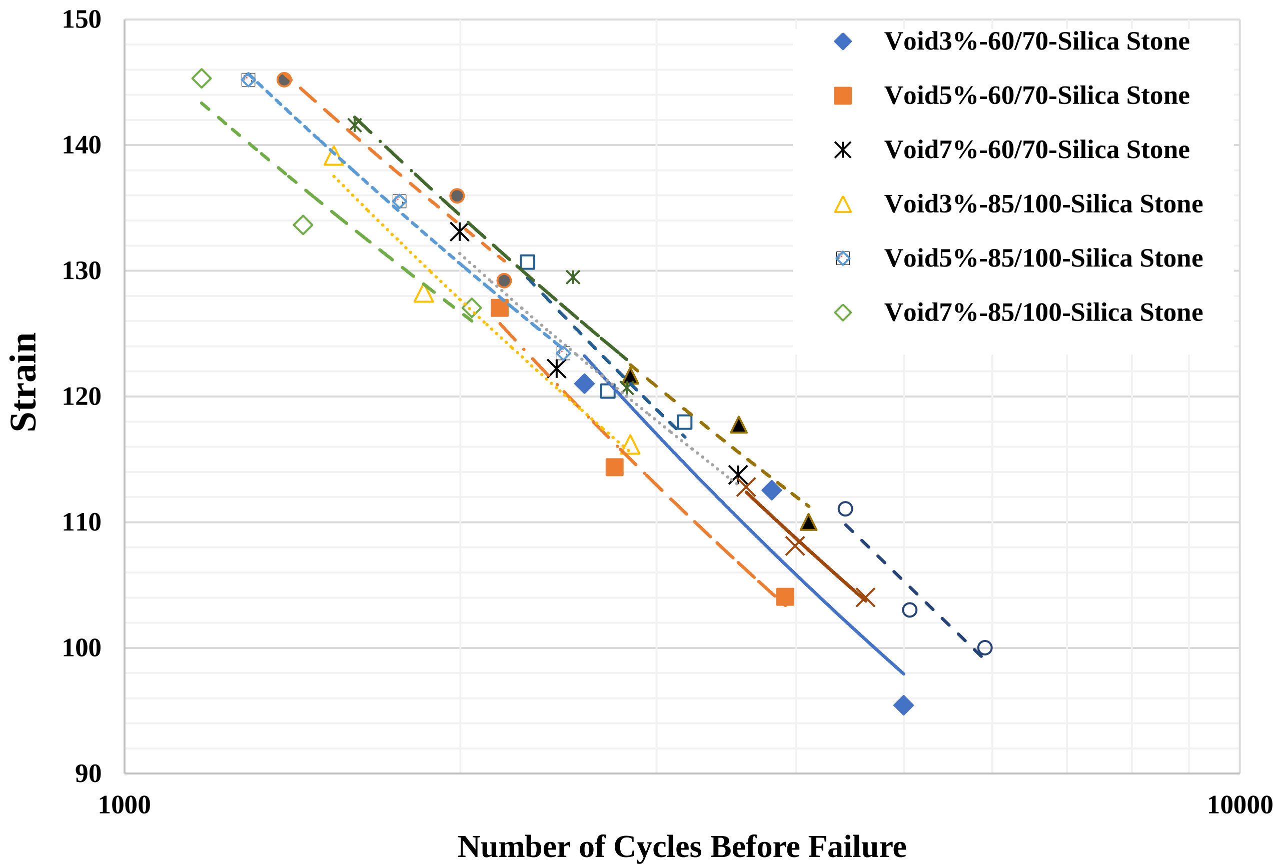


**Fig. 9.** Failure cycle number versus ultimate strain for asphalt samples of this study.

## 5. Proposing a model to describe hot asphalt mixture fatigue behavior

Numerically analyzing the experimental results provided by previous studies, a model was proposed to predict and describe the fatigue behavior of HMAs under various loading, materials, and air void contents. As mentioned, the fatigue life of an asphalt sample depends on the strain levels. In this paper, the power equation is employed to obtain different models (Eq. 1). A nonlinear power function is one of the best functions to fit fatigue data, as widely applied in previous studies.

$$N = a\varepsilon_t^b \tag{1}$$

Where N denotes the failure cycle number, $\boldsymbol{\varepsilon_t}$ stands for the tensile strain, and $\boldsymbol{a}$ and $\boldsymbol{b}$ are the coefficients of the fatigue life model. Table 5 represents the model for each sample based on the experimental data. Figs. 3, 4, 7, and 10 reflect the proposed model for each sample along with the corresponding coefficient of determination ($R^2$). Comparing the models indicates the difference in the fatigue behavior of samples built with different aggregates and air void contents. These models can be used to describe and predict the fatigue life of asphalt mixtures.

**Table 5.** The proposed models for the hot mix asphalt samples.

| Type of bitumen and aggregate | Air Void | Nonlinear regression model | $R^2$ |
|---|---|---|---|
| 60/70-Silica Stone | 3 | $N_f = 1910\ \epsilon_t^{-0.349}$ | **0.9004** |
| | 5 | $N_f = 1627.5\ \epsilon_t^{-0.333}$ | **0.9795** |
| | 7 | $N_f = 967.63\ \epsilon_t^{-0.263}$ | **0.9509** |
| 85/100-Silica Stone | 3 | $N_f = 1107.7\ \epsilon_t^{-0.284}$ | **0.9725** |
| | 5 | $N_f = 875.63\ \epsilon_t^{-0.25}$ | **0.9959** |
| | 7 | $N_f = 733.41\ \epsilon_t^{-0.231}$ | **0.9213** |
| 60/70- Lime Stone | 3 | $N_f = 2255.5\ \epsilon_t^{-0.36}$ | **0.9177** |
| | 5 | $N_f = 1605\ \epsilon_t^{-0.325}$ | **0.9836** |
| | 7 | $N_f = 983.88\epsilon_t^{-0.262}$ | **0.8979** |
| 85/100-Lime Stone | 3 | $N_f = 1503.3\ \epsilon_t^{-0.317}$ | **0.9012** |
| | 5 | $N_f = 965.35\ \epsilon_t^{-0.259}$ | **0.9298** |
| | 7 | $N_f = 812.86\ \epsilon_t^{-0.238}$ | **0.9411** |

## 6. Conclusion

This study attempted to investigate the fatigue behavior of HMAs, as commonly used paving materials in Iran, at different air void contents and low temperatures utilizing indirect tensile tests to find whether they can be employed to improve pavement durability. In summary, the following results were obtained:

1. According to the Marshall test, the optimal bitumen content of lime-aggregated samples was 5.5, while that of the silica-aggregated samples was 5%. The difference arose from the more porous structure of lime aggregates.
2. The results indicated that the bitumen penetration factor is of greater significance than the air void content

factor regarding fatigue life. The 60/70 bitumen-built sample with the air void content of 5% had a longer fatigue life compared to the 85/100 bitumen-built sample with the air void content of 3% at the same stress level.

3. It can be concluded that lime aggregates are more fatigue-resistant than silica aggregates. The difference in their failure cycle numbers is more noticeable at higher loading stresses. Comparing the obtained results demonstrated that the effect of the air void content rise is higher than that of the aggregate type on fatigue life reduction. The fatigue life of the silica aggregate mixture with the air void content of 3% was higher than the lime aggregate mixture with the air void content of 5%.

4. According to the proposed models of indirect tensile test, the highest fatigue life was obtained for the lime aggregate mixture made from 60/70 bitumen with the air void content of 3%, while the lowest fatigue life was derived for the silica aggregate mixture made from 85/100 bitumen with the air void content of 5% at 5°C.

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